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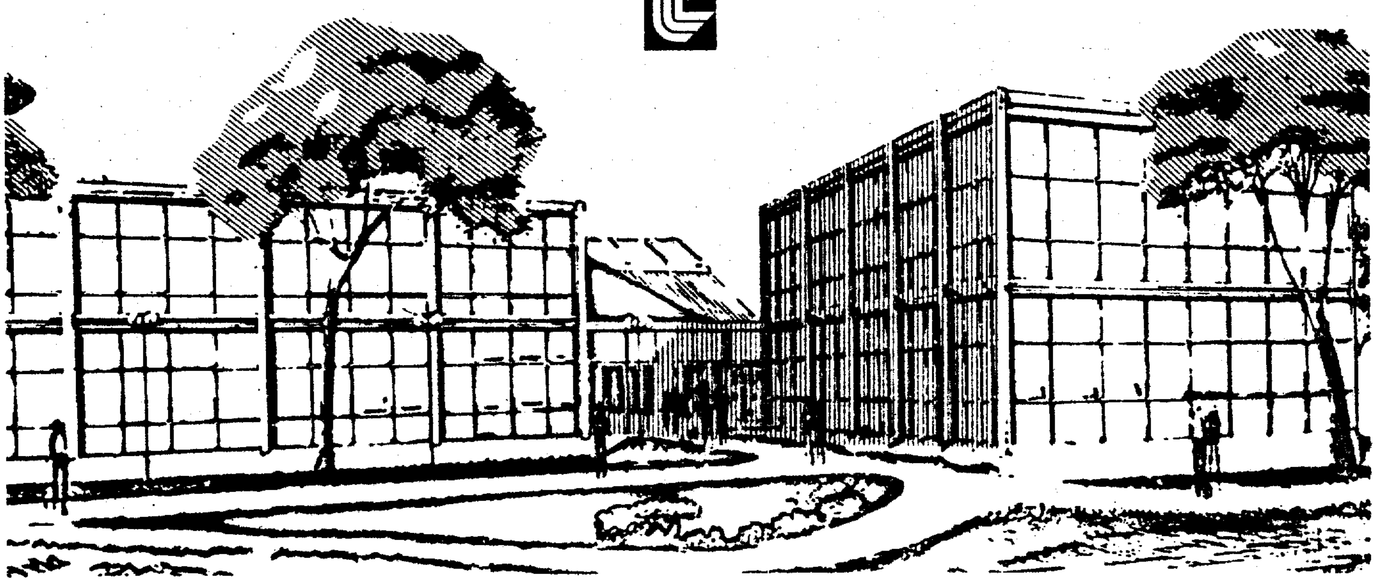
For presentation at the UNITAR Conference on Long-Term Energy Resources, Montreal, Canada, November 26 to December 7, 1979.



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A COMPUTATIONAL SITE SCREENING METHODOLOGY FOR WIND ENERGY*

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INTRODUCTION

The cost of establishing a wind power generation facility and the dependence of available power on the mean cube of the wind speed make it desirable to perform a preliminary, objective site screening using existing data. Variations of the winds in both space and time will have to be considered in the analysis. The analyst must be able to reduce large numbers of observations to a manageable subset and, since there is little chance that data will be available at all sites of interest, he must be able to infer winds at these locations. It is particularly important that in complex terrain the methods used in predicting winds reflect the topographically induced enhancement that is known to occur.

The objective, computational site screening methodology developed at Lawrence Livermore Laboratory addresses the various aspects of this problem as they relate to the identification and quantification of wind energy resources within regions with linear dimensions of about 100 km. The process may be divided into a series of logical steps as outlined by Knox (1979):

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Step 1. Wind Data Acquisiton.

This step involves the acquisition and data basing of all surface and upper air wind data from climatological sources for the region of interest. If there are sources of information from special networks these data are also obtained. In normal wind prospecting and site selection situations such special studies are frequently nonexistent.

Step 2. Determination of characteristic wind patterns.

Since the models used to determine winds throughout the region of interest are, in general, time consuming to run (1 to 3 minutes per data set) the full data base must usually be reduced to some more usable subsets. It is possible that this process may take place in two separate phases.

In the first, one or two patterns characteristic of the wind climatology of the region are determined. These are obtained through a subjective study of all the existing data and will provide, through use of a spatial analysis code, a preliminary assessment of potential sites.

In the second phase, a more detailed objective analysis is made of the data. Here, data for at least a year are examined by month or season in order to establish representative sets of observations for these periods. The methods for pattern recognition for regional flow were developed at LLL and are based on the method called Principal Components Analysis (PCA). PCA generates empirical eigenvectors from the data and, using their time dependent expansion coefficients, types days with similar wind fields and produces a best fit to these patterns. This information is stored, as is the sequence of typical days and their frequency of occurrence.

Step 3. Spatial wind field analysis.

For each characteristic day, whether determined in the first or second phase of Step 2, diagnostic regional calculations are performed using the typed days and detailed topographic information. For this purpose the LLL developed computer model MATHEW is used. This produces a spatial distribution, in three dimensions, of the winds in the region for each typed day.

Step 4. Annual wind energy potential.

Using the wind speeds computed by MATHEW and the day-type frequency distributions from PCA, wind energy potential may be computed for the region as a whole and wind speed duration curves may be computed for specific sites within the region.

In this paper we will describe the manner in which we have implemented these ideas in order to perform objective site screening. We will use data from the island of Oahu, Hawaii for illustration. Surface data used for the preliminary assessment were collected by stations operated by the National Weather Service (NWS) and the military services. Upper air observations came from the windward side of Oahu during World War II.

Data for the more detailed analysis are from the two year period, August 1976 - July 1978 and were provided by cooperating agencies such as NWS, the military, the University of Hawaii and four sites instrumented by LLL. A summary of this data may be found in the LLL Oahu surface wind data base report (Shinn, et al., 1979). The locations of the observation stations are plotted on a map of the island in Fig. 1.

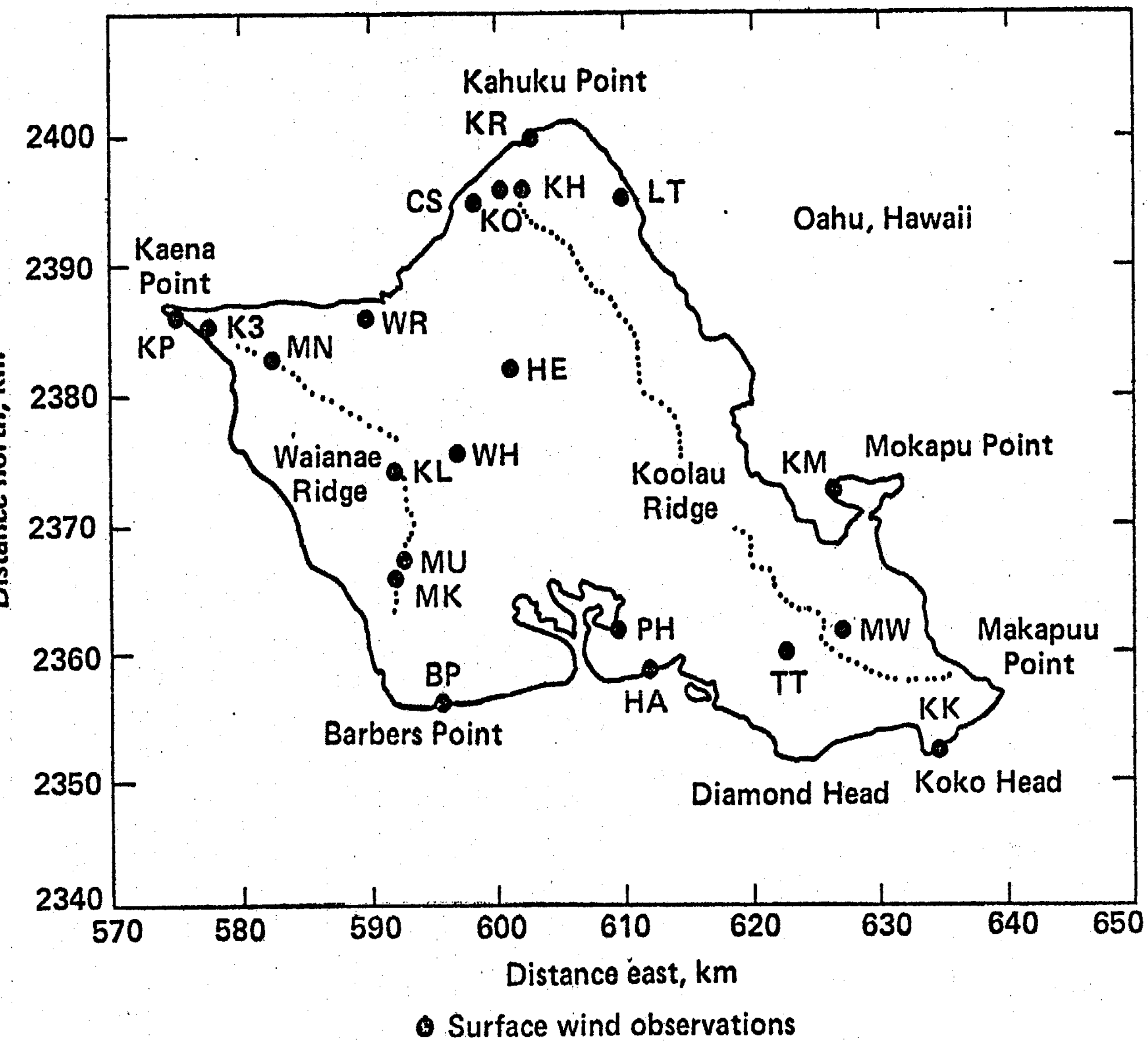


FIGURE 1. Locations of the surface wind observation stations used in the wind energy siting calculations.

- o The relative magnitudes of the associated eigenvalues can be used to rank-order the eigenvectors in terms of decreasing significance in representing the data.
- o The most significant eigenvectors can be identified with physically important patterns in the original data.
- o The primary eigenvectors provide a highly efficient basis set for approximating the original observed data.

A detailed discussion of principal components analysis and its application to wind field data may be found in Hardy and Walton (1978).

The data to be analyzed consist of horizontal wind velocities measured simultaneously at a number of geographic locations. Using complex notation, an Hermetian matrix can be formed from sums of products of these data. The eigenvectors of this matrix constitute an efficient basis set in terms of which all of the observations may be represented. The corresponding eigenvalues, because they are equal to the mean square of the expansion coefficients, give the relative importance of each eigenvector in representing the data. The dominant eigenvector, in general, looks like an actual wind field that is observed in the region. Fig. 2 shows the primary eigenvector for August 1976 on Oahu.

Since the primary eigenvector reflects the main spatial characteristics, its expansion coefficients can be expected to reflect the temporal variations of the wind field (e.g. diurnal changes). Fig. 3 shows the primary eigenvector expansion coefficients for the first six days of August 1976 on Oahu. We have developed a method, using these expansion coefficients, of identifying recurring diurnal wind flow patterns. Once this has been done, a month can be divided into subgroups of similar days and their frequency of occurrence recorded. While most months will have several different types of days, we have found that the

SCREENING PREMISES

The foundation of the site screening methodology rests upon our ability to identify recurrent temporal and spatial wind field patterns and to predict winds through the use of objective diagnostic models. Specifically, the premises are:

- Recurring patterns will be observed when looking at the diurnal behavior of the wind field over a region for a month. The month can then be represented by a few subsets of days with similar diurnal patterns. In our study, each month's data were described by a single subset. Days not like those in the subset were not included in the subsequent analysis.
- Because all days in a subset look similar, we assume that a subset of days for a given month of data can be replaced by a single typical day. Weighted averages of these days will give the same statistics as those for the subsets above.
- Statistical information can be inferred at sites without data by using MATHEW predictions based on input from the typical day representing each month.

OBJECTIVE IDENTIFICATION OF TYPICAL WIND PATTERNS

To determine the main characteristics of regional wind field patterns, a tool is needed that will reduce large groups of data. We have chosen to use the method of Principal Components Analysis (PCA) as the basis for such a process. PCA produces a complete set of orthogonal eigenvectors in terms of which the original data may be expressed. Some of the advantages of this kind of representation are:

- The eigenvectors and principal components are determined from the original data and are derived by an objective mathematical procedure.

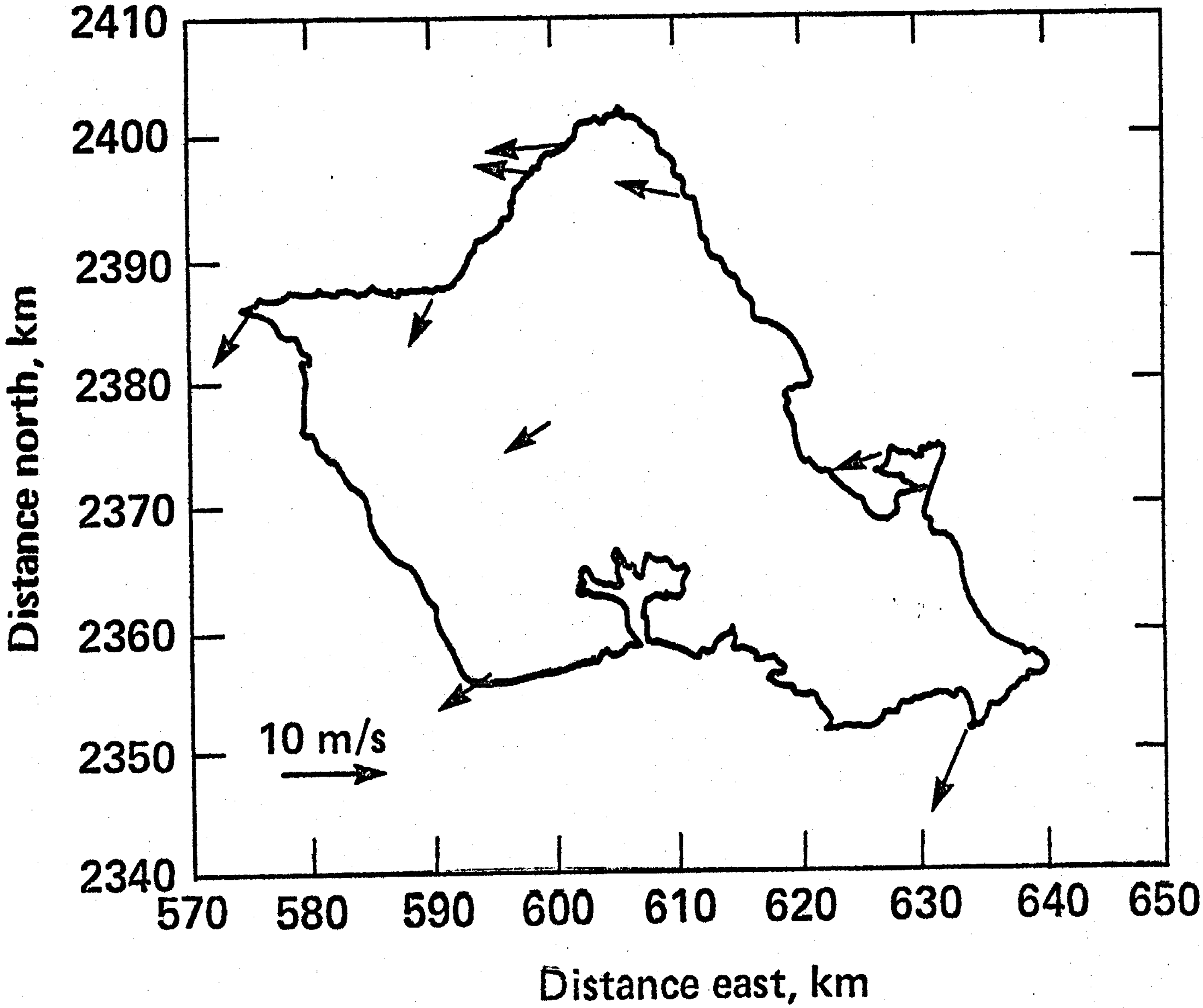
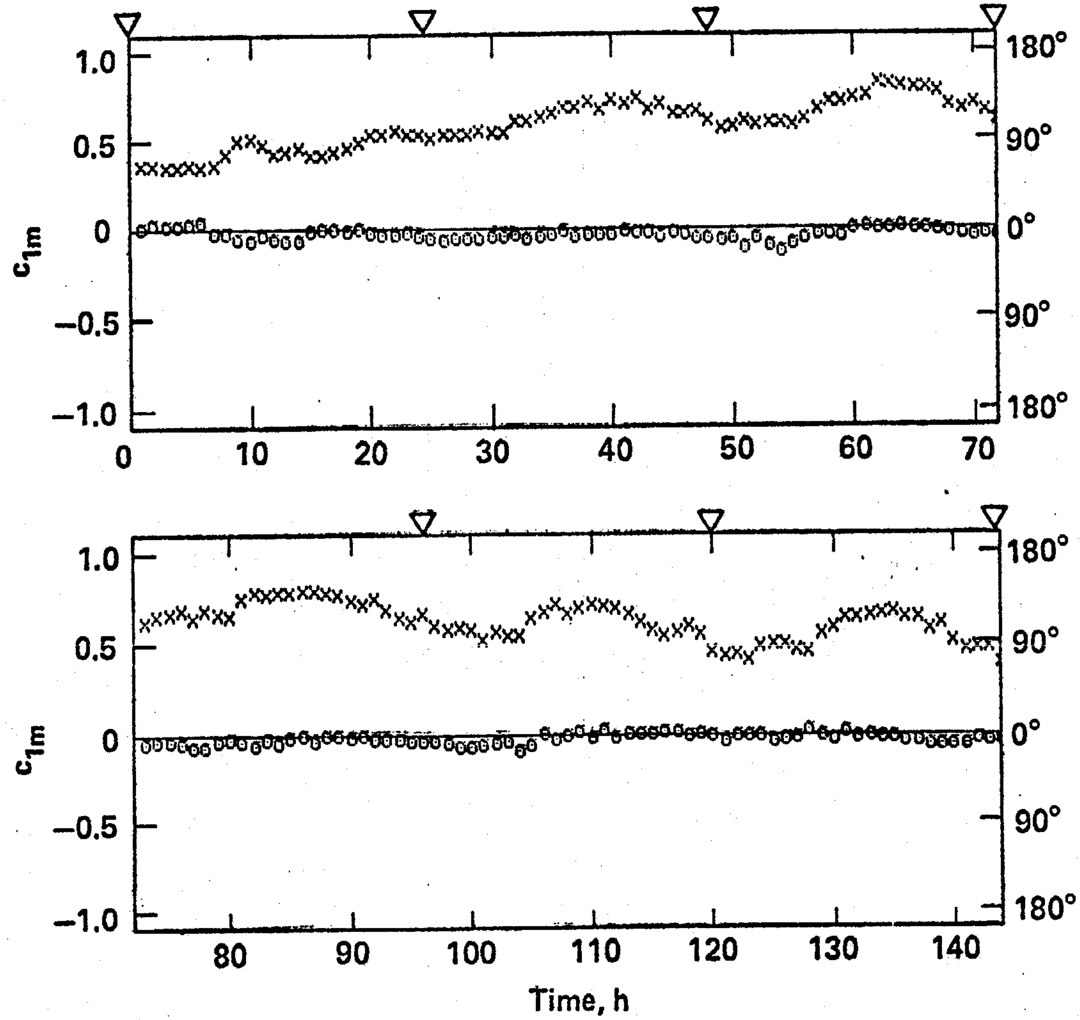


FIGURE 2. Primary eigenvector obtained for August 1976 from data on the island of Oahu, Hawaii.

FIGURE 3. Primary eigenvector expansion coefficients for the first six days of August 1976 for data from Oahu, Hawaii. Magnitude and argument of c_{1m} are plotted respectively as x and o.



most frequently occurring subgroup produces an adequate statistical representation of the month. Thus, we have reduced 365 days of data for a year to twelve typical days.

OBJECTIVE INTERPOLATION OF WIND FIELD DATA

Since, especially in the early stages of the site screening process, there may not exist wind data at all points that show promise for wind power siting, it is necessary to have a method of objectively estimating winds at these locations. To this end we have used the MATHEW model developed by Sherman (1978). The program, based on the work of Sasaki (1958, 1970a,b), requires that deviations of winds estimated from observations be minimized (adjusted) in the least squares sense while satisfying the condition of non-divergence.

Fig. 4 - Fig. 6 illustrate the steps in this process. Fig. 4 gives the observational data provided as input to MATHEW. The data are interpolated onto the MATHEW grid producing an initial flow pattern in three dimensions. Fig. 5 shows flow lines and isotachs of this interpolated field 60m above topography. Strong divergences and convergences are often present in this field. Finally, after adjustment, a non-divergent field will result as is shown in Fig. 6 where we again see flow lines and isotachs at 60m.

A WIND ENERGY ASSESSMENT

As an illustration of the steps given in the introduction we present an assessment of the wind energy potential for Oahu using historical records and the first year's data base (8/76-7/77).

FIGURE 4. Wind velocity data adjusted to 60m above topography using a 0.2 power law.

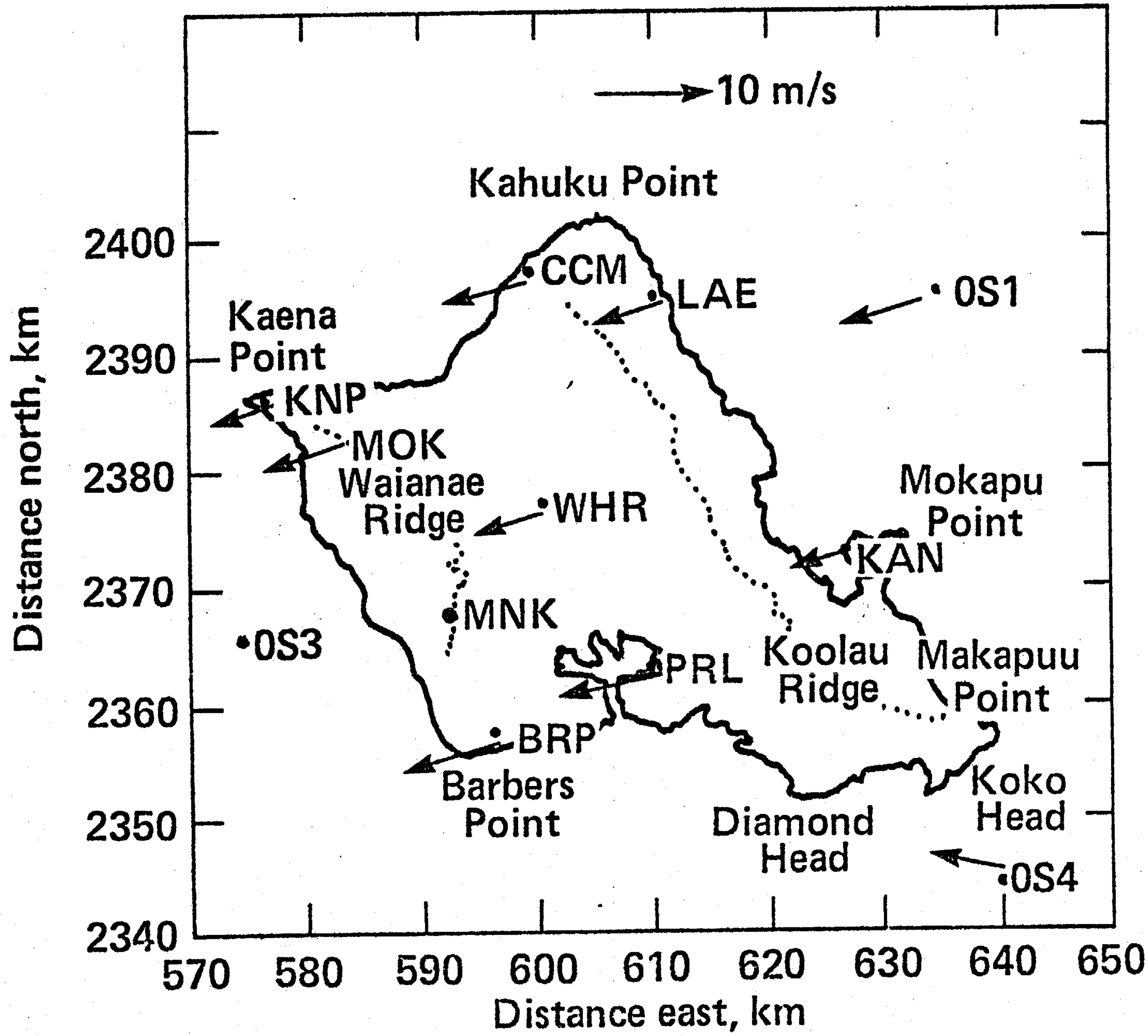


FIGURE 5. Interpolated flowlines and isotachs of wind velocity data (m/s) 60 meters above topography, contour interval is 5.0 m/s.

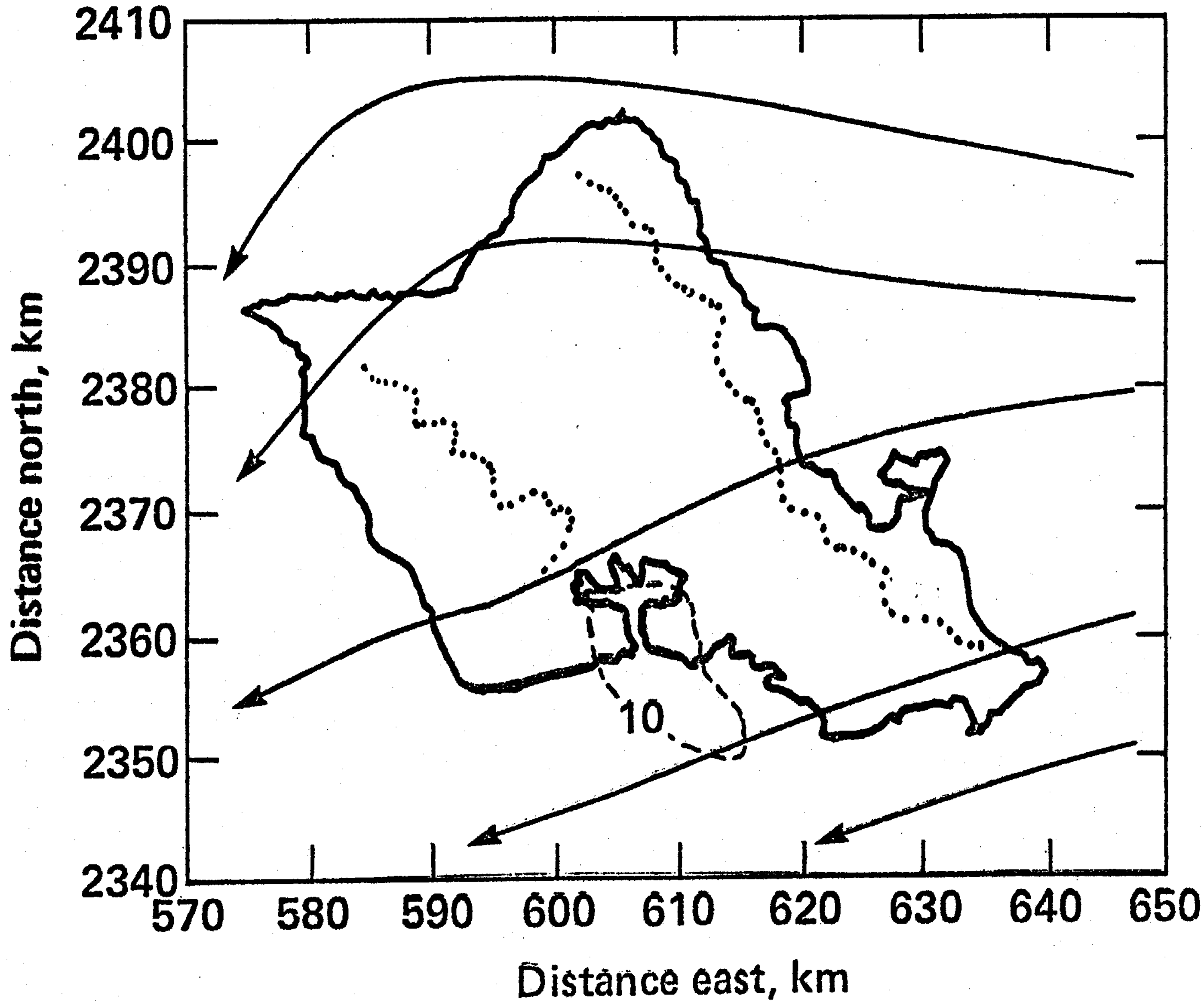
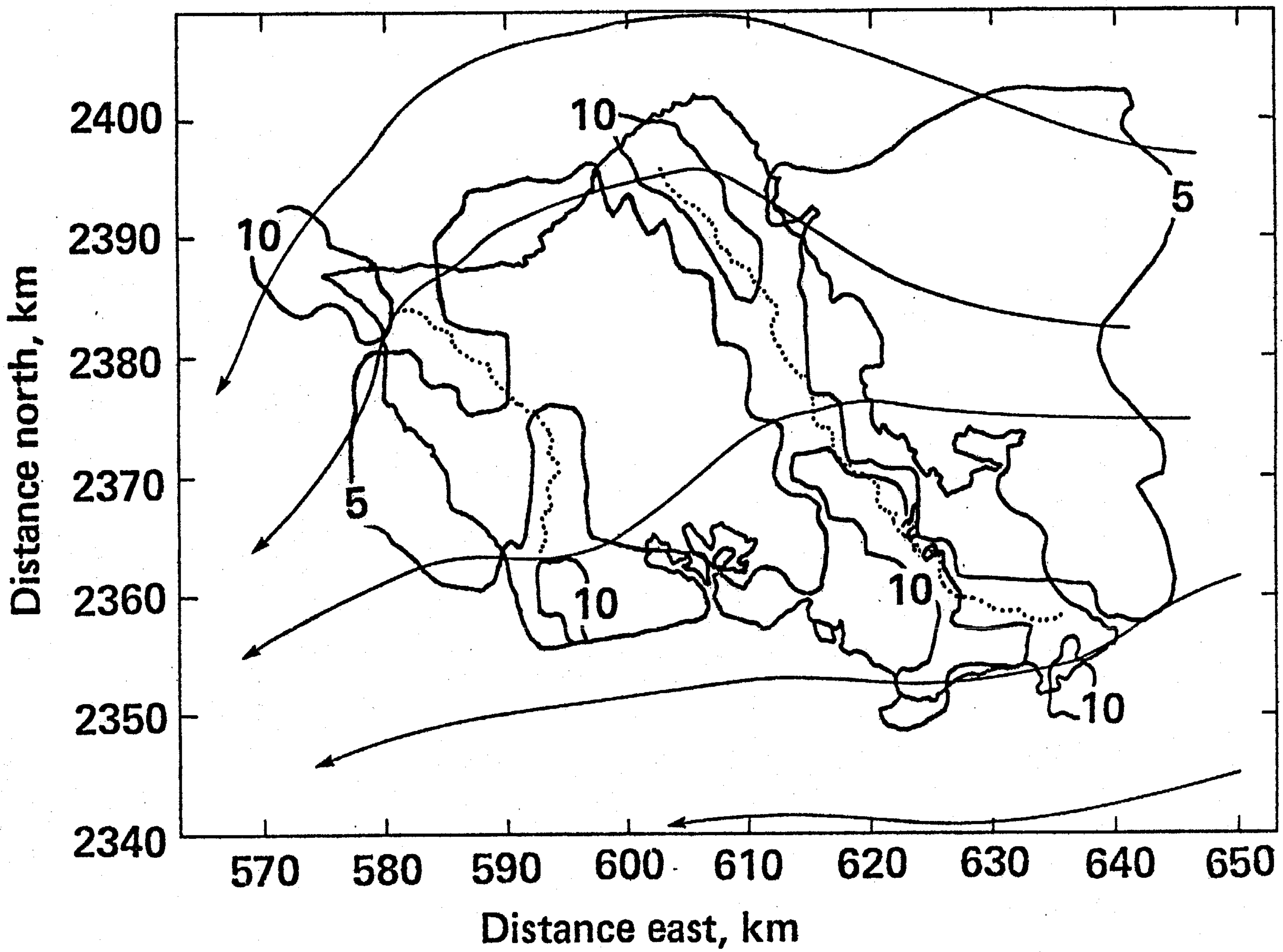


FIGURE 6. Adjusted flowlines and isotachs of wind velocities (m/s) 60 meters above topography. Contour interval is 5.0 m/s.



PRELIMINARY ASSESSMENT

Prior to the establishment of the full data base, a preliminary identification of regions of potential wind enhancement is desirable. This constitutes Steps 2 add 3 in the introduction, making use of long term historical records only.

Historical records extending back for a number of years are available for nine stations on Oahu, many of which are not now active. From a five year set, we abstracted (Knox, et al., 1976) wind data for 1400 LST for all five July months and contructed a composite of the most frequent wind speed and direction for each station (Step 2). These data, shown in Fig. 7, provided the input winds to MATHEW (Step 3). Note that there is only one station in the northern part of the island and this is strongly affected by terrain.

Topographic contours of the island are shown in Fig. 8 at a contour interval of 100m. These contours are based on the average elevation at a model resolution of 1.5 km in the horizontal. The digitized topography of the island as resolved by MATHEW is depicted in Fig. 9, where the vertical scale is greatly expanded to make terrain features more apparent. The view in Fig. 9 is from the southeast. The computational results appear in Fig. 10 as flow lines of the adjusted winds and isotachs of wind speed. The areas between contours have been shaded for added clarity. This map shows speed maxima on the corners of the island with minima in the central valley and immediately up and down wind to major topographic barriers. The significant wind maximum on the Kahuku Hills was a striking early find in that the northeast portion of the island was devoid of climatological measurements. This indicates the power of MATHEW as a diagnostic tool in the initial siting work. The results of this kind of study may identify sites at which more detailed

FIGURE 7. Historical wind data for the most frequent wind speed and direction at 2 p.m. LST in July at observing stations on Oahu, Hawaii.

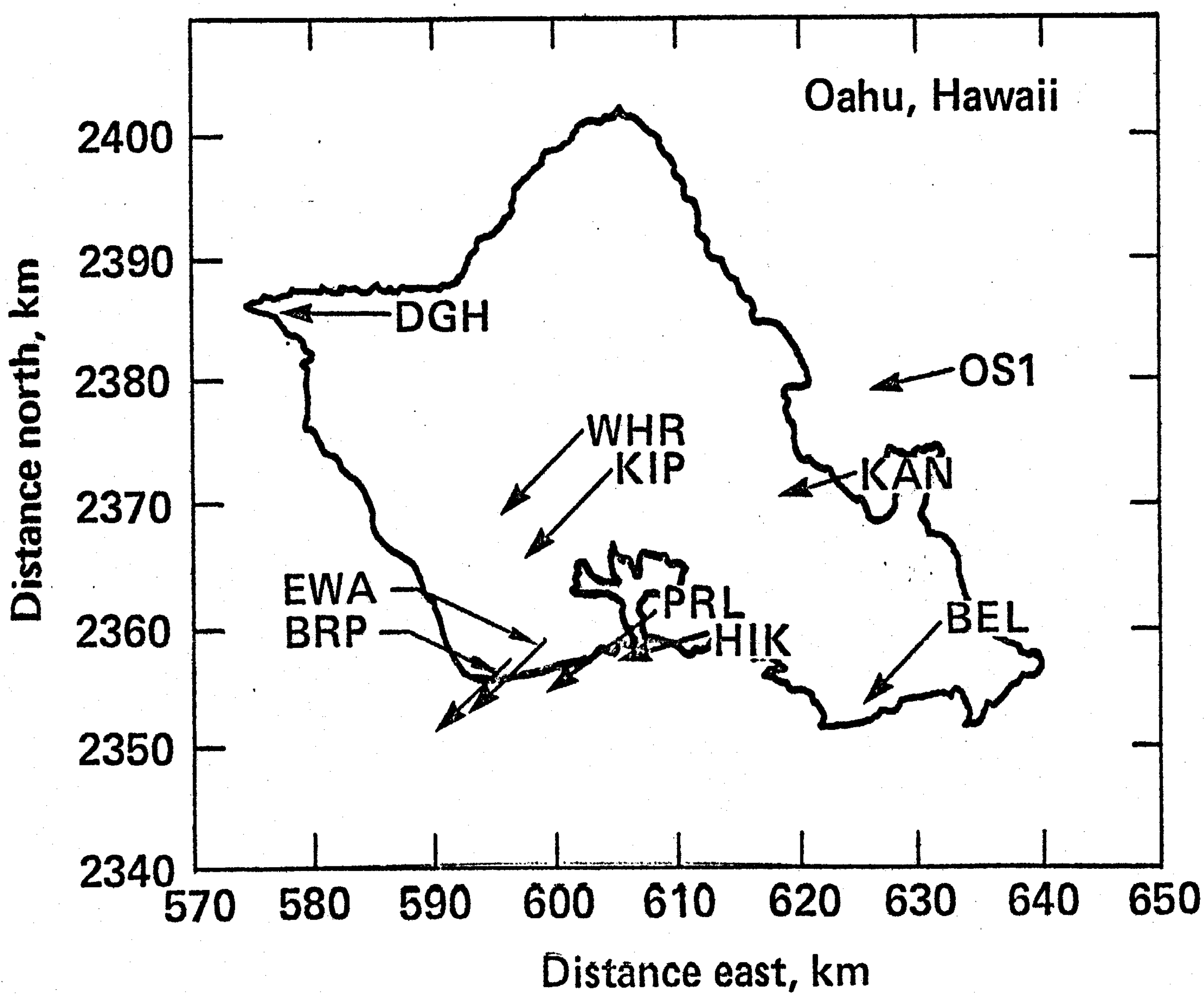
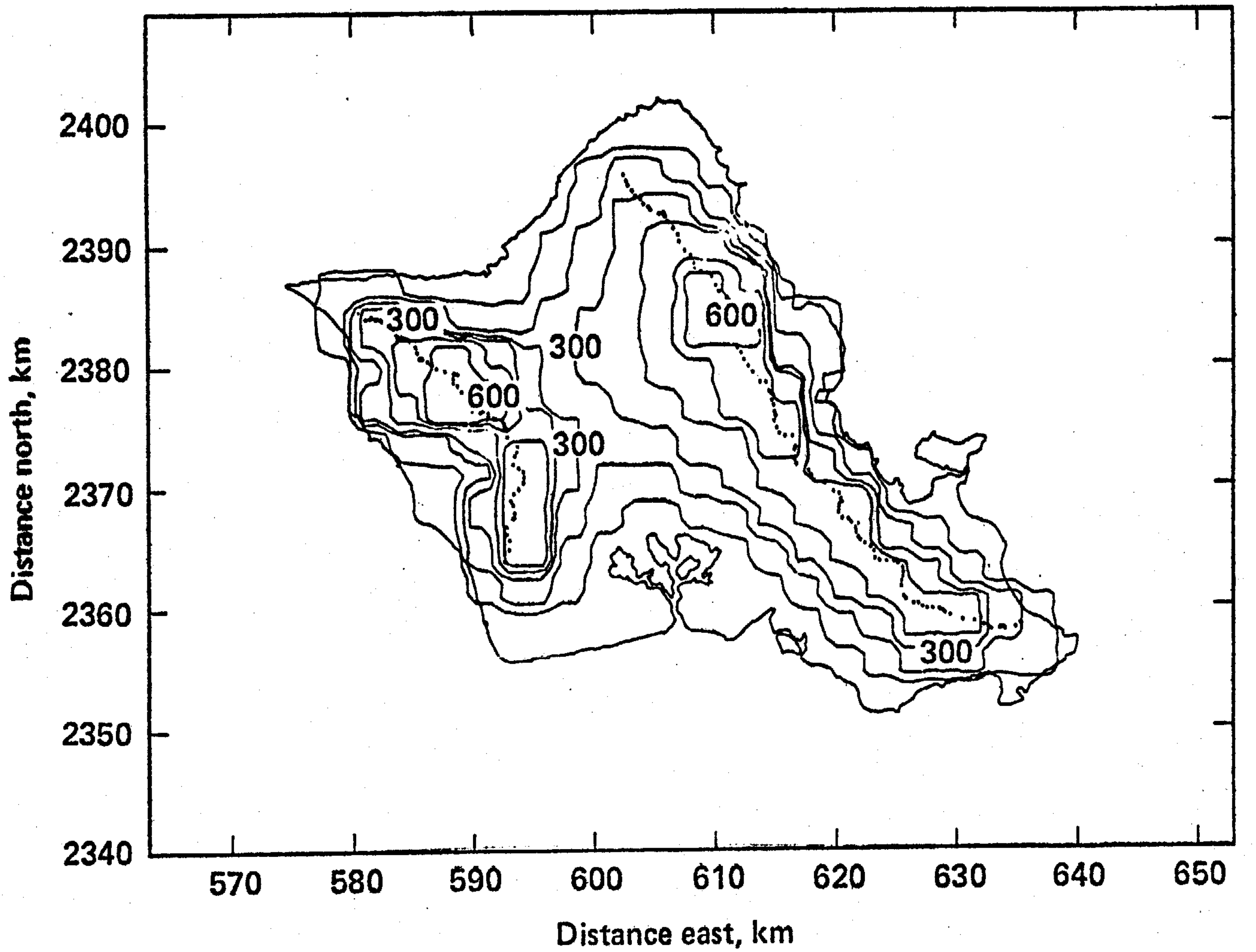


FIGURE 8. Contours of model topography for the island of Oahu, Hawaii at a contour interval of 100m and and horizontal resolution of 1.5 km.



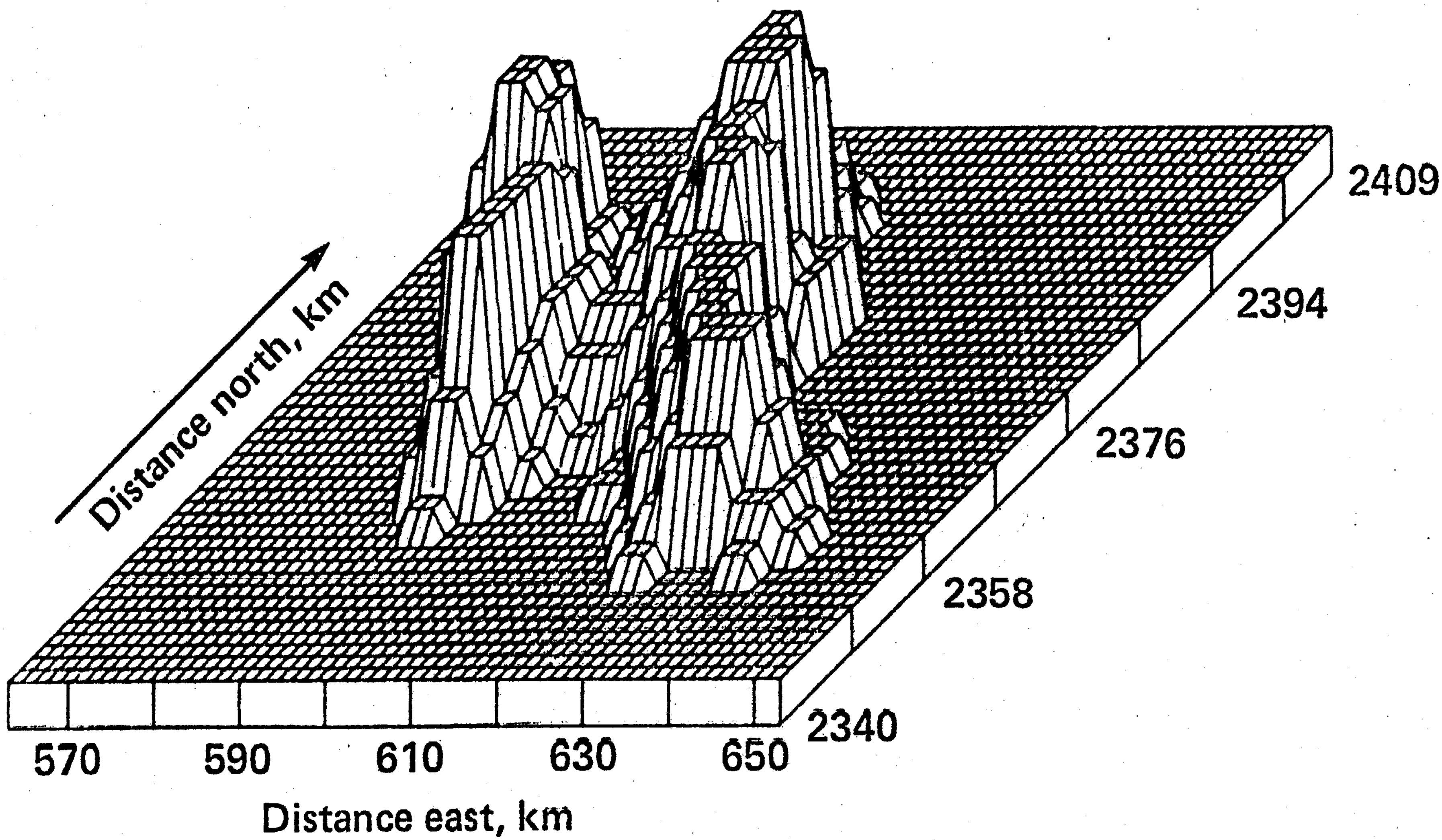
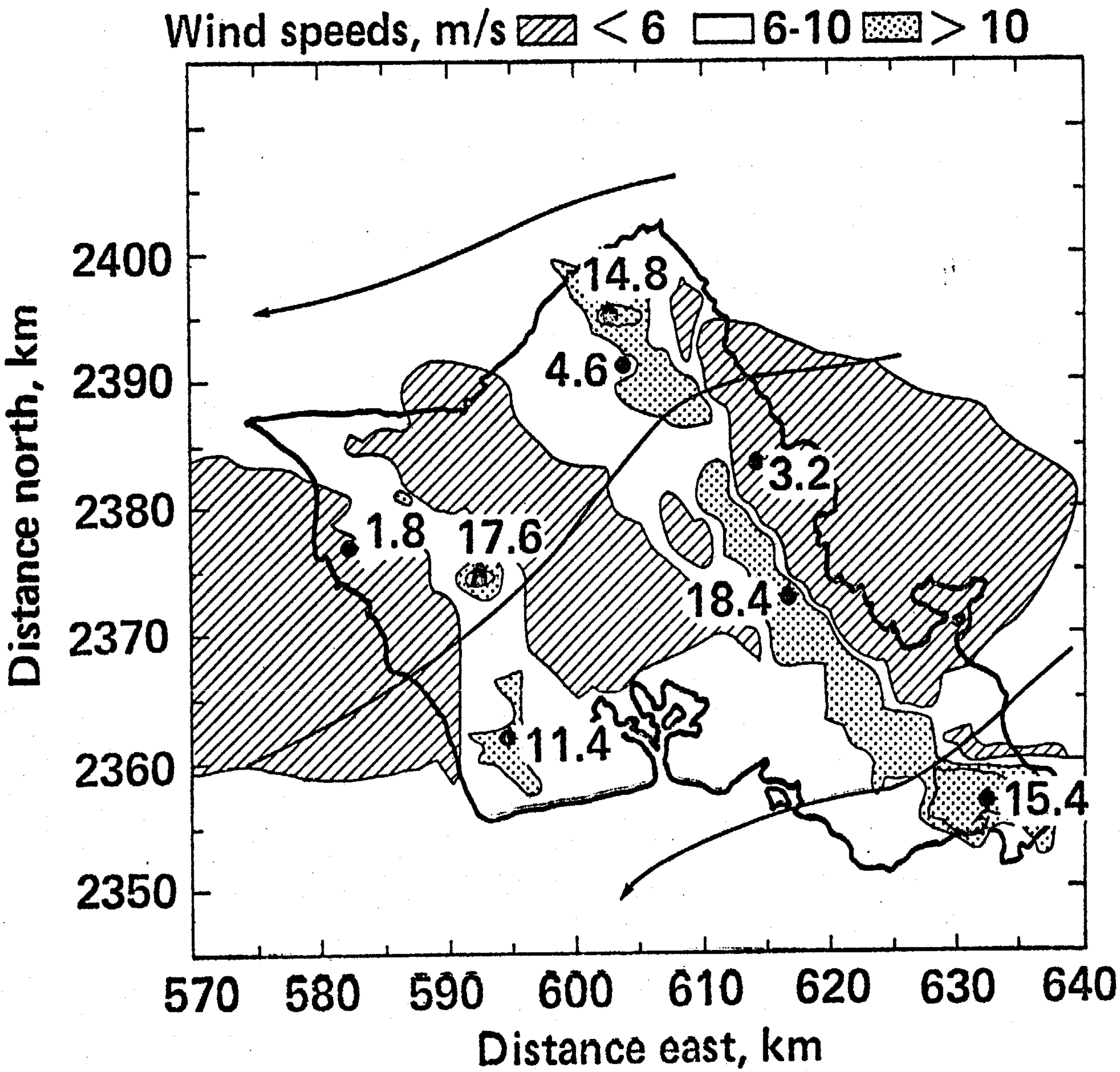


FIGURE 9. Digitized topography of Oahu, Hawaii as seen from the southeast. The vertical scale is greatly expanded with respect to the horizontal scale.

FIGURE 10. Adjusted flowlines and isotachs of winds 150m above topography based on historical data only. Contour interval is 5.0 m/s.



analysis is merited. It was, in fact on the basis of such results that the choice of location of four LLL supported wind measurement stations was made.

DETAILED ASSESSMENT

The detailed assessment can be carried out when the full data set has been completed and the preliminary assessment had identified likely wind energy sites, (in this case, Kaena Point and Kahuku Hill).

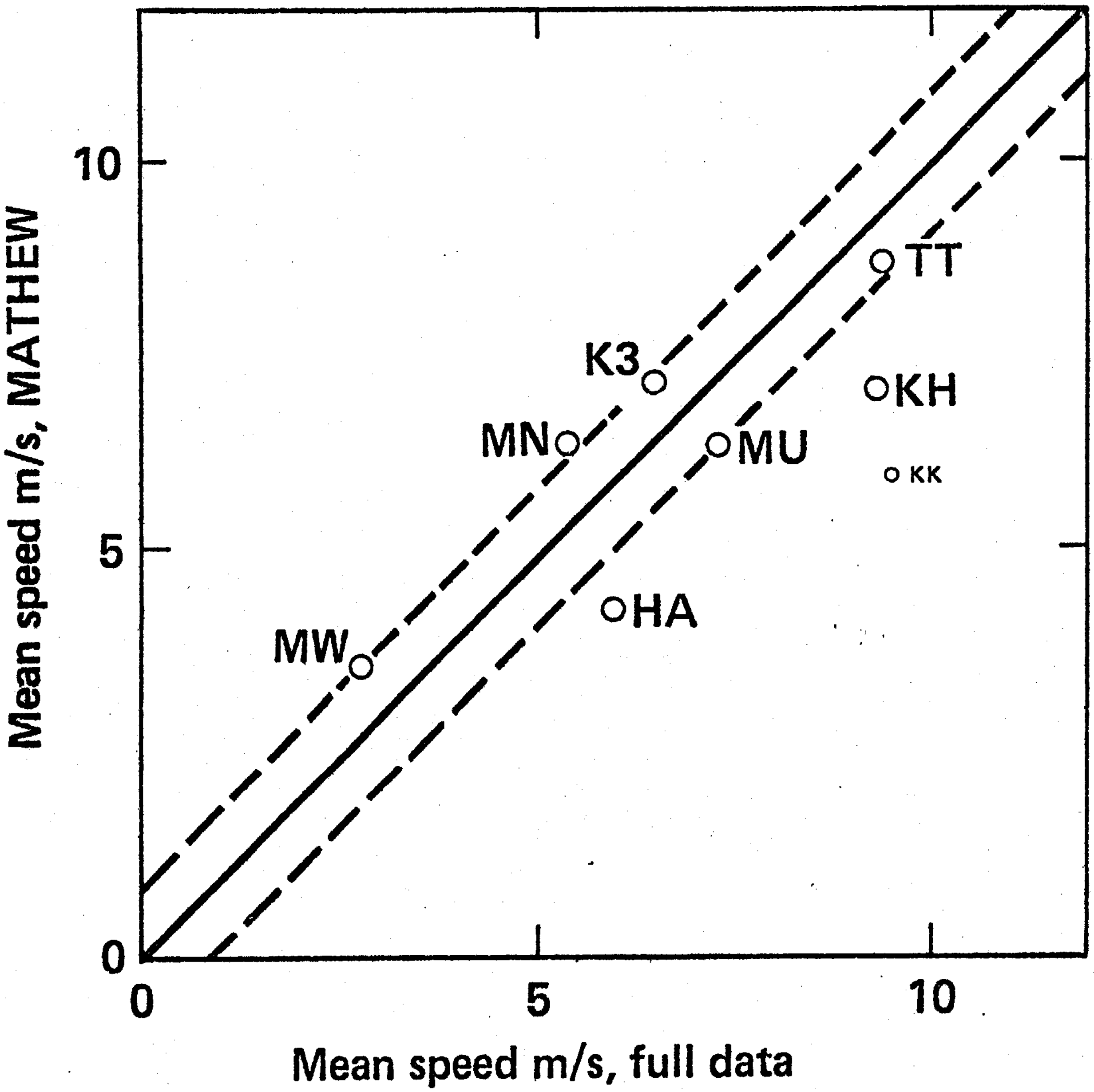
Using the PCA codes, a typical day was selected for each month and its frequency of occurrence noted (Step 2). These results are shown in Table 1. Data for every third hour (2:00 a.m., 5:00 a.m., etc.) of each of these days was used as input to MATHEW (Step 3). Thus, 96 MATHEW runs were required to perform the year's assessment. We have found that, in fact, only two samples per day are needed (24 MATHEW runs) for adequate statistics. For the purpose of verification, data from eight sites, including Kaena Point tower (K3) and Kahuku Hill (KH), were withheld.

TABLE 1. DAYS REPRESENTING THE MOST FREQUENT OCCURRING DIURNAL PATTERN AND THE NUMBER OF DAYS REPRESENTED FOR TYE YEAR 8/76-7/77

Month	8/76	9/76	10/76	11/76	12/76	1/77	2/77	3/77	4/77	5/77	6/77	7/77
Typical day	2	11	13	16	6	12	6	18	7	7	11	11
No. of days represented	29	25	23	21	20	23	7	25	19	24	21	30

Before continuing to the annual assessment, Fig. 11 is presented as part of the verification of our site screening methodology. In this figure we have plotted annual mean wind speed for all verification sites,

FIGURE 11. Scatter diagram of mean wind speed based on MATHEW predictions vs. mean wind speed based on the full data set.



obtained using the PCA/MATHEW codes, versus that from the full data set. The Koko Head (KK) site presents an interesting situation. Although strong winds are measured at this station, it is located on a topographic feature too small to be resolved on the MATHEW grid. For this reason enhancement is not predicted here. However, since it is comparatively small it would not be considered as a likely location for a large scale wind power installation.

Step 4, the annual wind energy potential can be presented in two ways, one giving a regional picture, the other providing details at specific sites. First, contours of annual power at some level above topography may be calculated from the MATHEW predicted wind fields and the PCA computed frequency of occurrence table. Fig. 12 shows contours of average annual wind power (w/m^2) at 50m above terrain. The contours reflect the same general structure as the wind speed contours produced in the preliminary assessment, performed in 1976, that identified the key enhancement area at Kahuku Hill.

A second way of looking at the MATHEW results is to compute wind speed statistics at sites that show particular promise. Annual mean wind speeds (or mean power if desired) can be computed from this information. Fig. 13 and Fig. 14 show the wind speed duration curves for Kaena Point and Kahuku Hill respectively. The duration curves obtained from the full year's data set have been included for the purpose of comparison. Here, the degree of agreement between the predicted and observed duration curves constitutes another check on the ability of our methodology to provide statistical information where it is needed. The extremely good fit at Kaena Point is probably fortuitous while the curve shape at Kahuku Hill is worse than at most sites. Deviations in curve shape are the result of features of the MATHEW model which are undergoing study and modification.

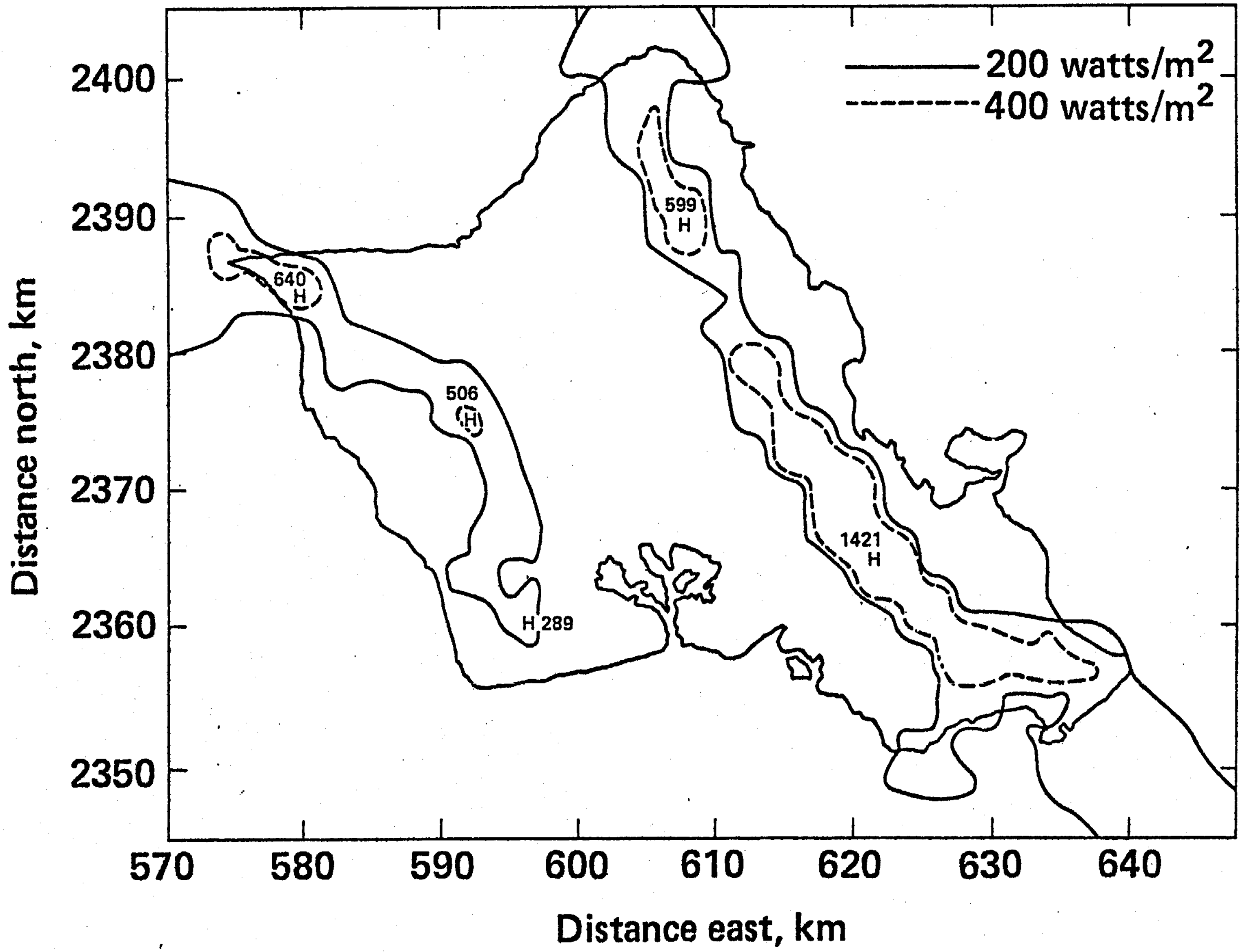


Figure 12. Annual average windpower (w/m^2) at 50m on Oahu, Hawaii for the period 8/76-7/77.

FIGURE 13. Duration curves at Kaena Point (30 ft.) for 8/76-7/77 comparing weighted MATHEW predictions with the full data set.

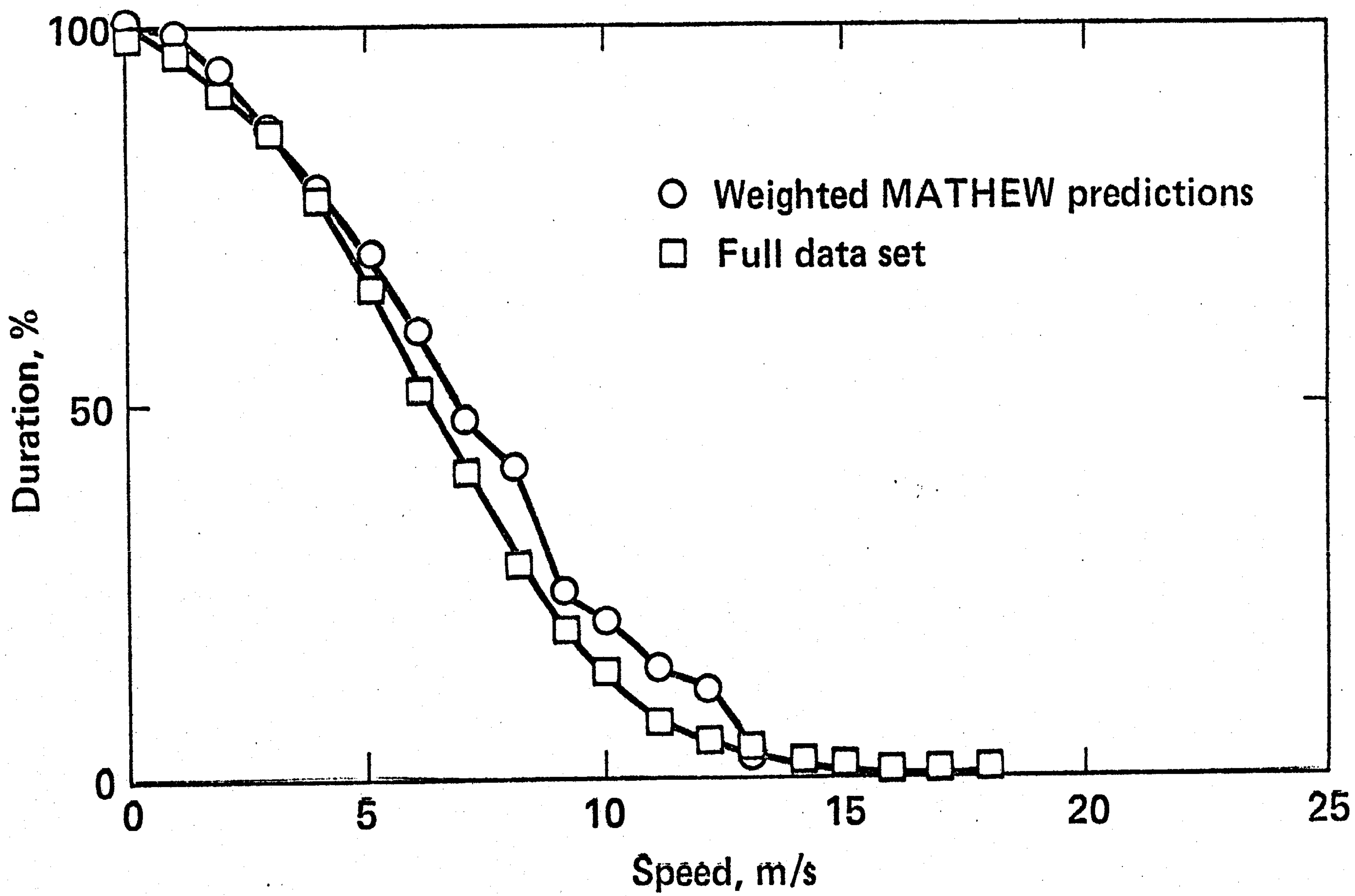
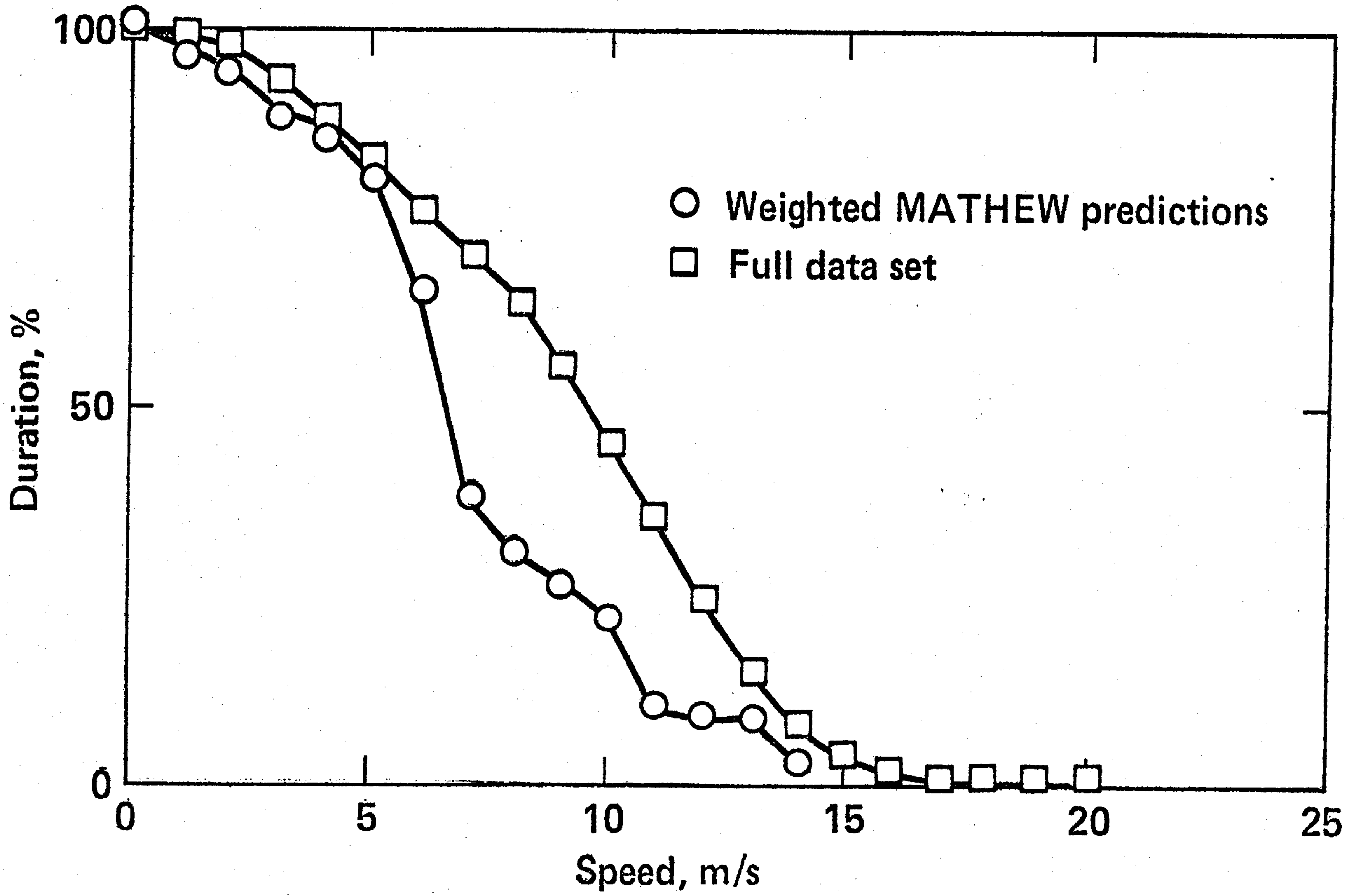


FIGURE 14. Duration curves at Kahuku Hill for 8/76-7/77 comparing weighted MATHEW predictions with the full data set.



CONCLUSIONS

The wind energy planner is faced with the task of siting costly generating equipment that is sensitive to variations of wind speed. In addition, an extensive wind measurement program is itself costly and time consuming. While there is no substitute for a properly run measurement program, early site screening can provide benefits in saved time and money.

The LLL site screening methodology based on the MATHEW three-dimensional regional flow model and the PCA wind field pattern characterization codes has been developed, verified, and illustrated in this study. Not only are these codes able to provide regional wind power maps, but they also provide reasonable wind speed statistics at specific locations containing sites with terrain enhancement. The site methodology has the capability to make an initial identification of potentially useful wind energy sites which may then, when identified, be investigated through the effective installation of wind measurement instrumentation. A new version of MATHEW that is expected to improve specific site predictions is undergoing testing at this time.

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